

RESEARCH PAPER

Effect of Potassium Iodide Combined with Plant Extract on the Corrosion Inhibition of R410Al99 Aluminum Alloy in an Acidic Medium

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ARTICLE INFO

Article History:

Received 24 December 2025

Accepted 20 March 2026

Published 01 April 2026

Keywords:

Adsorption film

Electrochemical polarization

FTIR

Green chemistry

Localized attack

ABSTRACT

Potassium iodide-assisted corrosion inhibition of R410Al99 aluminum alloy in 1 M H_2SO_4 was investigated using a methanolic *Citrullus colocynthis* leaf extract. Combined inhibitor solutions contained 2 M KI and 3–15 mL/L extract and were tested at 10–40 °C. Open-circuit potential, Tafel polarization, cyclic polarization, FTIR, FESEM, EDS, and AFM were used to evaluate electrochemical behavior and surface-film formation. The Tafel response was strongly dependent on concentration and temperature. The highest apparent Tafel-derived inhibition efficiency was 99.77% at 6 mL/L and 40 °C, where the corrosion-current density decreased from 2.5128×10^{-3} to 5.6875×10^{-6} A/cm². The 9 mL/L condition at 30 °C, selected for detailed surface characterization, achieved 98.11% efficiency, with $E_{\text{corr}} = -0.59813$ V, $i_{\text{corr}} = 4.1399 \times 10^{-5}$ A/cm², and a recalculated polarization resistance of 245.96 $\Omega\cdot\text{cm}^2$. Quasi-steady OCP values for the best-performing concentration at each temperature agreed reasonably with the corresponding Tafel corrosion potentials. Cyclic polarization retained positive hysteresis at all temperatures, showing that high uniform-corrosion inhibition did not completely eliminate localized attack. FTIR band shifts supported participation of O–H/N–H, C–H, aromatic/conjugated, and C–O groups in a mixed organic–inorganic film. EDS showed recovery of Al from 9.9 to 64.4 at.%, reduction of O from 72.9 to 29.1 at.%, disappearance of detectable S, and the presence of K and I on the protected surface. AFM and FESEM indicated a dense, chemically modified, heterogeneous protective layer with reduced obvious pitting. The results demonstrate effective KI-assisted adsorption and surface protection in strongly acidic media.

How to cite this article

Ismael Ibrahim A, Abd AN. Effect of Potassium Iodide Combined with Plant Extract on the Corrosion Inhibition of R410Al99 Aluminum Alloy in an Acidic Medium. J Nanostruct, 2026; 16(2):2569-2580. DOI: 10.22052/JNS.2026.02.096

INTRODUCTION

R410Al99 is a commercially pure aluminum alloy containing at least 99 wt.% Al. Its low density, ductility, conductivity, and inherent oxide film support its use in electrical, packaging,

architectural, and non-structural applications. Strong mineral acids, however, can destabilize the native film and accelerate both uniform and localized dissolution. Plant-derived inhibitors have therefore been examined as renewable

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alternatives for protecting aluminum in acidic media, including sulfuric-acid systems [1-10].

Citrullus colocynthis contains oxygen- and nitrogen-bearing phytochemicals capable of interacting with metallic surfaces. Earlier work reported inhibition by methanolic *C. colocynthis* extracts and related fractions on aluminum, copper, and carbon steel [11-15]. In acid solution, iodide can alter the interfacial charge distribution and promote the retention of organic inhibitor species. Similar KI-assisted effects have been reported for plant extracts on aluminum and other metals [16-18].

The present work evaluates a combined system comprising *C. colocynthis* leaf extract and 2 M KI for R410Al99 aluminum alloy in 1 M H₂SO₄. Extract concentrations of 3, 6, 9, 12, and 15 mL/L were examined at 10, 20, 30, and 40 °C. Electrochemical measurements were integrated with FTIR, EDS, AFM, and FESEM to relate inhibition performance to the chemical composition and morphology of the surface film.

MATERIALS AND METHODS

Materials and alloy composition

Analytical-grade sulfuric acid (96%, density 1.84 g/mL) was diluted with distilled water to prepare 1 M H₂SO₄. Methanol (≥99.8%, Merck, Germany) was used for extraction, acetone (99.9%, ROMIL) was used for degreasing, and potassium iodide (KI; molar mass 166.00 g/mol) was used to prepare a 2 M solution. R410Al99 aluminum alloy served as the working material. Its optical-emission-spectroscopy specification is summarized in Table 1.

Preparation of the plant extract

Leaves of *C. colocynthis* were repeatedly washed with distilled water, air-dried under

ambient conditions for five days, and ground. A 150 g portion of the powdered material was continuously extracted with 750 mL methanol in a Soxhlet apparatus at 65 °C for 8 h. The resulting methanolic extract was used as the inhibitor stock and was characterized by FTIR to identify the functional groups available for surface interaction [19].

Specimen preparation

The alloy was sectioned by wire cutting into specimens measuring approximately 1 cm × 1 cm × 1.5 mm. Exposed faces were mechanically polished to a uniform finish, rinsed with distilled water, degreased with acetone, dried, and stored in sealed containers before testing. The electrochemically exposed working area was 1 cm².

Electrochemical measurements

Measurements were performed with a Corrtest CS350M potentiostat/galvanostat in a three-electrode cell. R410Al99 was the working electrode, a saturated calomel electrode (SCE) was positioned approximately 1 mm from the exposed surface, and platinum served as the counter electrode. The open-circuit potential was monitored until a quasi-steady interfacial response was obtained. Tafel and cyclic polarization measurements were then recorded for the uninhibited 1 M H₂SO₄ blank and for solutions containing 2 M KI plus 3, 6, 9, 12, or 15 mL/L extract at 10, 20, 30, and 40 °C. [scan rate = 2v/s, potential limits = -3V, stabilization time = 900s, and number of replicate measurements = 3].

The Tafel-derived inhibition efficiency was calculated from the corrosion-current density using Eq. 1. Polarization resistance was recalculated using the Stern–Geary relationship in Eq. 2, with

Table 1. Nominal composition limits of R410Al99 aluminum alloy.

Element	Specification (wt.%)	Criterion
Al	99.0	minimum
Si	0.50	maximum
Fe	0.60	maximum
Cu	0.07	maximum
Zn	0.08	maximum
Ti	0.05	maximum
Other elements	0.04	maximum

β_a and β_c converted from mV/dec to V/dec before calculation.

$$IE (\%) = [1 - i_{\text{corr,inh}} / i_{\text{corr,blank}}] \times 100 \quad (1)$$

$$R_p = \beta_a \beta_c / \{2.303 i_{\text{corr}} (\beta_a + \beta_c)\} \quad (2)$$

where i_{corr} is the corrosion-current density, β_a and β_c are the anodic and cathodic Tafel slopes in V/dec, and R_p is expressed in $\Omega \cdot \text{cm}^2$ [20].

Surface characterization

FTIR spectra were recorded using a Shimadzu IRAffinity-1 instrument (laboratory code Fou24116). Surface morphology and elemental composition were examined using an Inspect F50 FESEM coupled with an Axia ChemiSEM/EDS system. AFM measurements were obtained

with a Nanosurf CoreAFM. The principal surface conditions evaluated were the polished alloy, the uninhibited alloy after exposure to 1 M H_2SO_4 , and the alloy protected with 9 mL/L extract + 2 M KI at 30 °C. The plant extract itself was also characterized by FTIR.

RESULTS AND DISCUSSION

Open-circuit potential behavior

The OCP profiles in Fig. 1 show strongly condition-dependent interfacial behavior. Most KI-containing solutions at 10 and 20 °C shifted toward more negative potentials than the blank, whereas the 30 and 40 °C profiles displayed concentration-specific positive and negative shifts. The absence of a monotonic concentration trend suggests dynamic competition among oxide dissolution, iodide adsorption, extract adsorption, and film

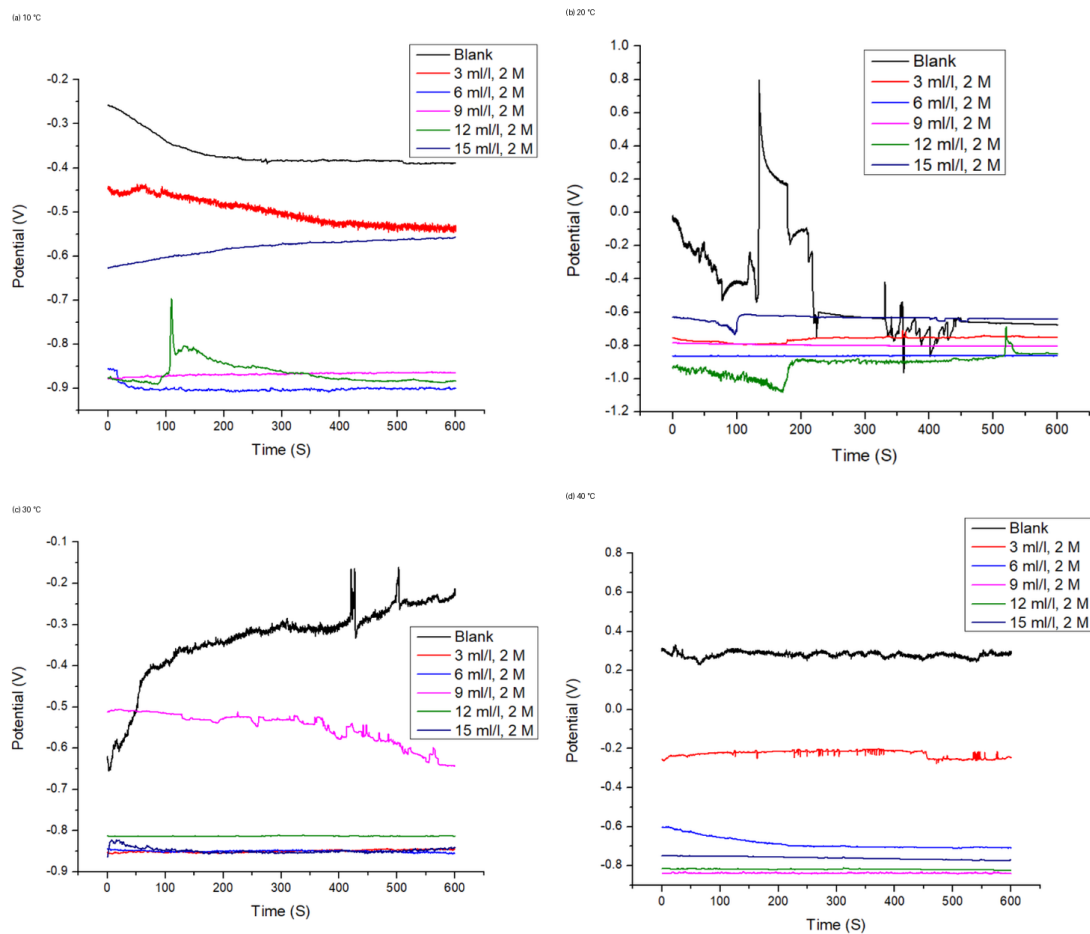


Fig. 1. Open-circuit potential of R410Al99 in 1 M H_2SO_4 containing 2 M KI and different *C. colocynthis* extract concentrations at (a) 10, (b) 20, (c) 30, and (d) 40 °C.

reorganization during immersion.

By the end of the 600 s OCP record, the blank and mixed-inhibitor systems had clearly separated potential levels. At 10 °C, the blank approached approximately -0.39 V vs SCE, whereas the 3, 6, 9, 12, and 15 mL/L solutions ended near -0.54 , -0.90 , -0.87 , -0.88 , and -0.56 V, respectively. At 20 °C, the blank settled near -0.68 V after a pronounced transient; the corresponding inhibited potentials were approximately -0.76 , -0.87 , -0.82 , -0.86 , and -0.64 V. At 30 °C, the blank moved to approximately -0.23 V, while all combined inhibitor solutions remained substantially more negative at about -0.85 , -0.86 , -0.65 , -0.82 , and -0.85 V. At 40 °C, the blank remained near $+0.28$ V, whereas the inhibited curves ended at approximately

-0.26 , -0.72 , -0.85 , -0.83 , and -0.78 V.

The transient excursion of the 12 mL/L trace at 10 °C, the large blank excursion at 20 °C, and the gradual negative drift of the 9 mL/L trace at 30 °C indicate continuing surface-film nucleation, disruption, and reorganization during immersion. OCP displacement alone does not quantify inhibition efficiency; nevertheless, the end-of-record potentials for the Tafel-optimum conditions were close to the independently fitted E_{corr} values: approximately -0.56 versus -0.58279 V at 10 °C/15 mL/L, -0.82 versus -0.82606 V at 20 °C/9 mL/L, -0.65 versus -0.59813 V at 30 °C/9 mL/L, and -0.72 versus -0.77457 V at 40 °C/6 mL/L. This agreement supports the internal consistency of the potential-time and polarization measurements

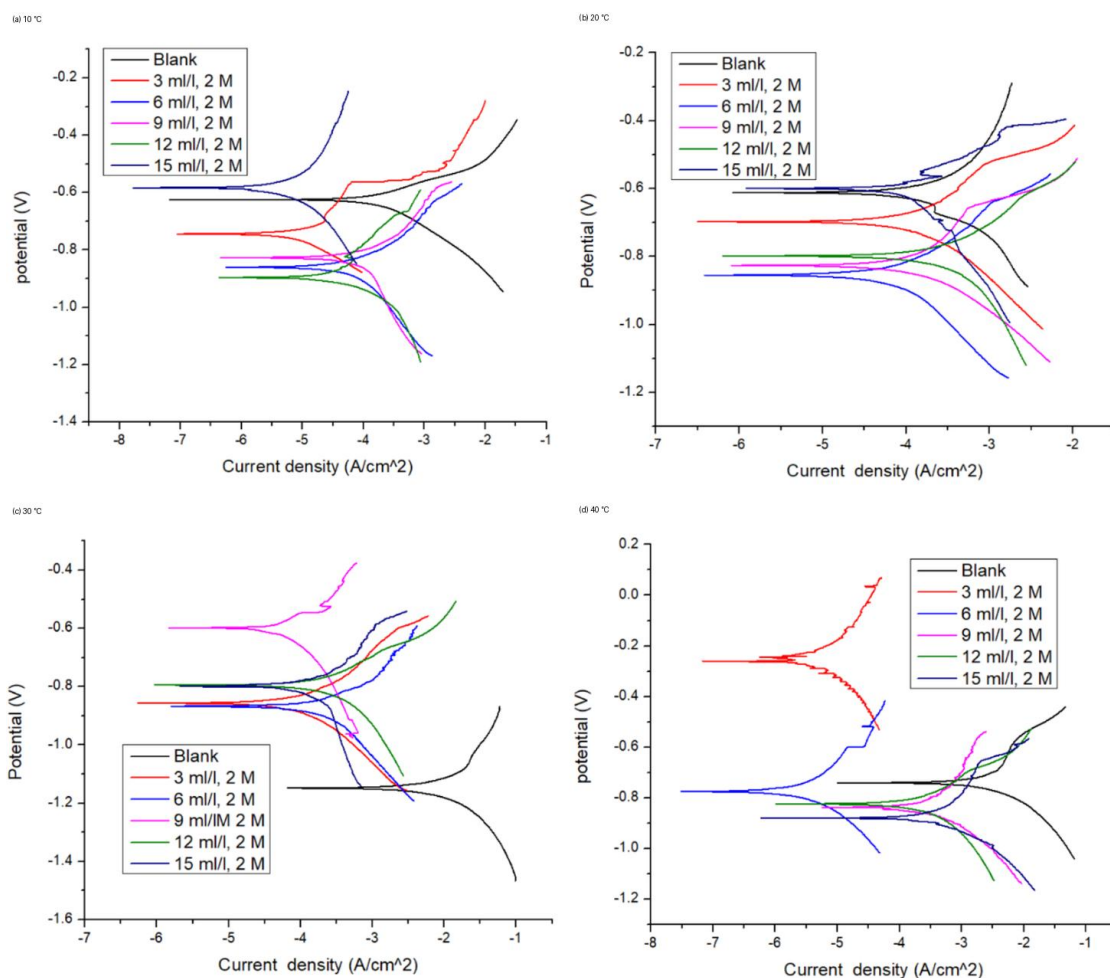


Fig. 2. Tafel polarization curves for R410Al99 in 1 M H₂SO₄ containing 2 M KI and different extract concentrations at (a) 10, (b) 20, (c) 30, and (d) 40 °C.

[21].

Tafel polarization

Fig. 2 and Table 2 demonstrate that the combined inhibitor markedly reduced i_{corr} at selected concentrations, but the response was non-monotonic. The best efficiencies at 10, 20, 30, and 40 °C were 98.55% (15 mL/L), 93.12% (9 mL/L), 98.11% (9 mL/L), and 99.77% (6 mL/L), respectively.

At the temperature-specific optimum, i_{corr} decreased from 1.3631×10^{-4} to 1.9813×10^{-6} A/cm² at 10 °C (15 mL/L), from 5.8338×10^{-4} to 4.0137×10^{-5} A/cm² at 20 °C (9 mL/L), from 2.1943×10^{-3} to 4.1399×10^{-5} A/cm² at 30 °C (9 mL/L), and from 2.5128×10^{-3} to 5.6875×10^{-6} A/cm² at 40 °C (6 mL/L). The corresponding recalculated R_p values were 5277.154, 237.408, 245.961, and 10891.795 Ω -cm², respectively. Thus, the optimum extract concentration shifted from 15 mL/L at 10 °C to 9 mL/L at 20–30 °C and 6 mL/L at 40 °C, confirming that inhibition performance depends on both concentration and temperature rather than on extract dose alone.

At 30 °C, the surface-characterization condition

of 9 mL/L extract + 2 M KI shifted E_{corr} from –1.1478 V for the blank to –0.59813 V, decreased i_{corr} from 2.1943×10^{-3} to 4.1399×10^{-5} A/cm², increased R_p from 3.449 to 245.961 Ω -cm², and produced 98.11% inhibition. Negative potential shifts predominated at 10 and 20 °C, positive shifts dominated at 30 °C, and both directions occurred at 40 °C. The combined system is therefore best described as condition-dependent mixed inhibition with anodic or cathodic predominance [22].

Cyclic polarization

The cyclic polarization curves in Fig. 3 exhibited positive hysteresis over much of the investigated range, confirming that localized corrosion susceptibility was not completely removed. Loop width and irregularity changed with temperature and extract concentration. Selected curves became narrower, indicating improved repassivation and reduced persistence of growing pits, whereas broad or irregular loops at other concentrations indicated unstable passive-film behavior. The combined inhibitor therefore improved localized-corrosion resistance in a concentration- and

Table 2. Tafel parameters for R410Al99 in 1 M H₂SO₄ containing 2 M KI and different *C. colocynthis* extract concentrations.

T (°C)	C (mL/L)	E_{corr} (V)	i_{corr} (A/cm ²)	β_a (mV/dec)	β_c (mV/dec)	R_p^* (Ω -cm ²)	IE (%)
10	Blank	-0.62428	0.00013631	70.120	90.044	125.577	0.00
10	3	-0.74367	9.4764e-06	81.712	136.780	2343.881	93.05
10	6	-0.85983	9.7804e-05	156.820	296.860	455.568	28.25
10	9	-0.82648	2.8293e-05	40.733	45.176	328.732	79.24
10	12	-0.89638	4.0079e-05	278.100	80.387	675.620	70.60
10	15	-0.58279	1.9813e-06	38.205	65.126	5277.154	98.55
20	Blank	-0.61173	0.00058338	555.180	402.960	173.789	0.00
20	3	-0.69760	8.6006e-05	144.020	107.200	310.271	85.26
20	6	-0.85465	0.00011073	192.350	276.170	444.612	81.02
20	9	-0.82606	4.0137e-05	44.122	43.660	237.408	93.12
20	12	-0.79815	7.938e-05	46.874	57.458	141.208	86.39
20	15	-0.59946	4.6925e-05	26.070	60.400	168.506	91.96
30	Blank	-1.14780	0.0021943	30.840	40.084	3.449	0.00
30	3	-0.85618	0.00016707	219.220	258.880	308.509	92.39
30	6	-0.86710	0.00045215	260.670	401.570	151.796	79.39
30	9	-0.59813	4.1399e-05	27.494	159.450	245.961	98.11
30	12	-0.79422	9.787e-05	41.942	66.165	113.889	95.54
30	15	-0.79865	4.5854e-05	52.749	33.318	193.368	97.91
40	Blank	-0.74045	0.0025128	284.670	113.810	14.050	0.00
40	3	-0.25764	8.3164e-05	408.110	325.550	945.520	96.69
40	6	-0.77457	5.6875e-06	337.980	246.870	10891.795	99.77
40	9	-0.83765	9.1847e-05	28.526	54.260	88.390	96.34
40	12	-0.82385	8.408e-05	54.368	58.707	145.774	96.65
40	15	-0.87973	0.00049093	301.850	124.470	77.948	80.46

* All nonblank solutions contained 2 M KI. IE was recalculated from Equation (1); R_p was recalculated from β_a , β_c , and i_{corr} after converting the Tafel slopes from mV/dec to V/dec. Blank = 1 M H₂SO₄ without extract or KI.

temperature-dependent manner.

Detailed comparison of the forward and reverse scans reveals distinct concentration effects. At 10 °C, the 6 and 15 mL/L curves showed the largest branch separation, whereas the 3 and 12 mL/L curves were comparatively more compact. At 20 °C, the 3 mL/L curve developed the broadest loop, and the 12 mL/L trace exhibited repeated current oscillations; the higher-concentration curves still showed positive hysteresis but with less extreme leftward displacement than the 3 mL/L condition. At 30 °C, the 3 mL/L curve displayed the closest forward–reverse alignment, while the 9, 12, and 15 mL/L curves were broader and more irregular, especially the oscillatory 12 mL/L trace. At 40 °C, the 3 and 9 mL/L curves were comparatively

more compact than the 6, 12, and 15 mL/L curves, although none showed complete overlap of the reverse and forward branches.

These observations show that the conditions giving the lowest uniform-corrosion current were not always those giving the best localized-corrosion response. The 9 mL/L + 2 M KI system at 30 °C produced 98.11% Tafel efficiency but retained a positive, irregular hysteresis loop; similarly, 6 mL/L at 40 °C reached 99.77% Tafel efficiency while a distinct reverse-scan separation remained. The combined inhibitor therefore strongly suppresses the average dissolution rate and can assist repassivation, but it does not provide complete immunity to pit initiation and propagation. The oscillatory segments are consistent with

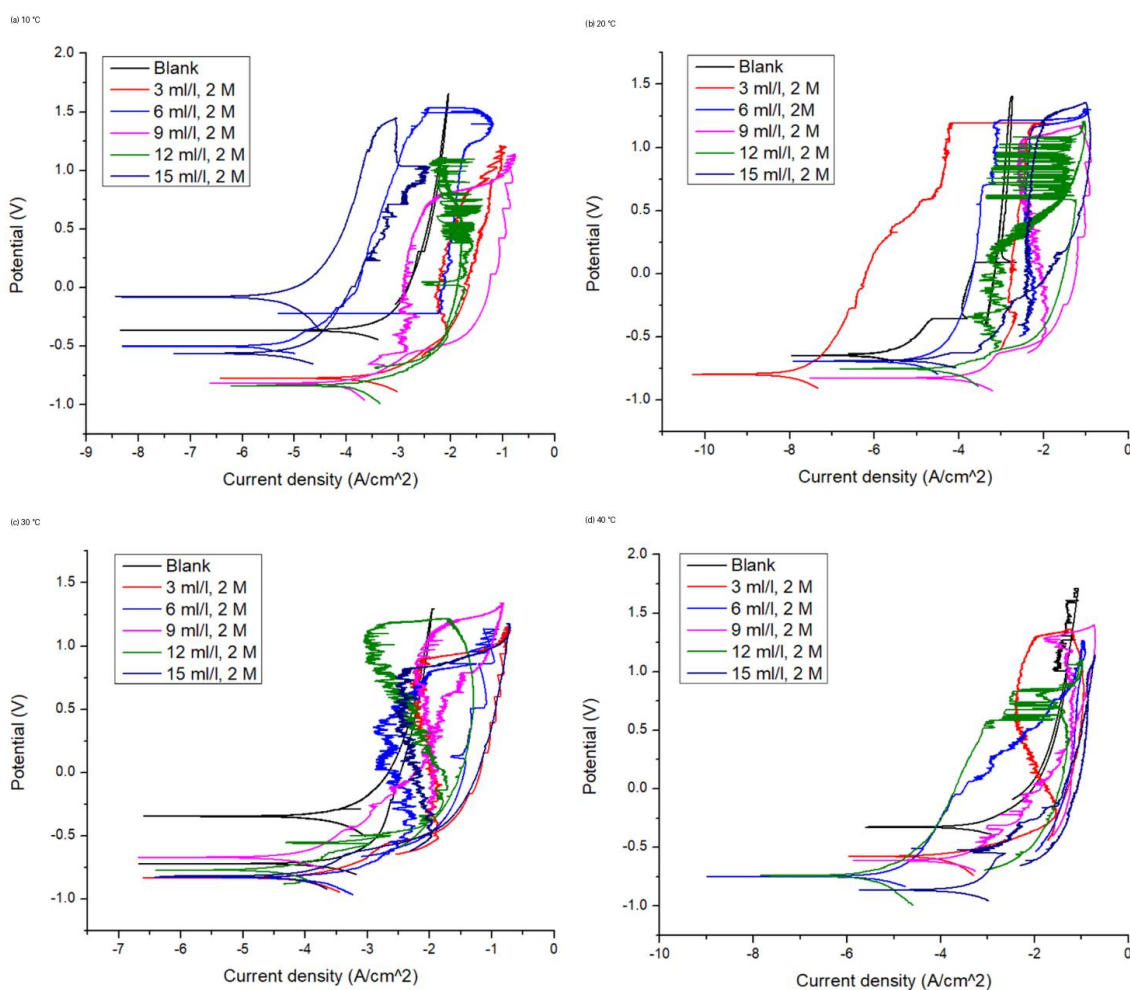


Fig. 3. Cyclic potentiodynamic polarization of R410Al99 in 1 M H₂SO₄ containing 2 M KI and different extract concentrations at (a) 10, (b) 20, (c) 30, and (d) 40 °C.

935, 691, and 606 cm^{-1} were consistent with sulfate/bisulfate-containing corrosion products. For the 9 mL/L + 2 M KI surface, broad O–H/N–H bands occurred at 3410 and 3205–3206 cm^{-1} ; C–H bands appeared at 3030, 2966, and 2940 cm^{-1} ;

and bands at 1647, 1555, 1537, 1128, and 1099 cm^{-1} reflected aromatic/conjugated and C–O-containing species. Changes over 941–406 cm^{-1} indicate reorganization of the oxide/hydroxide–sulfate layer in the presence of the extract and

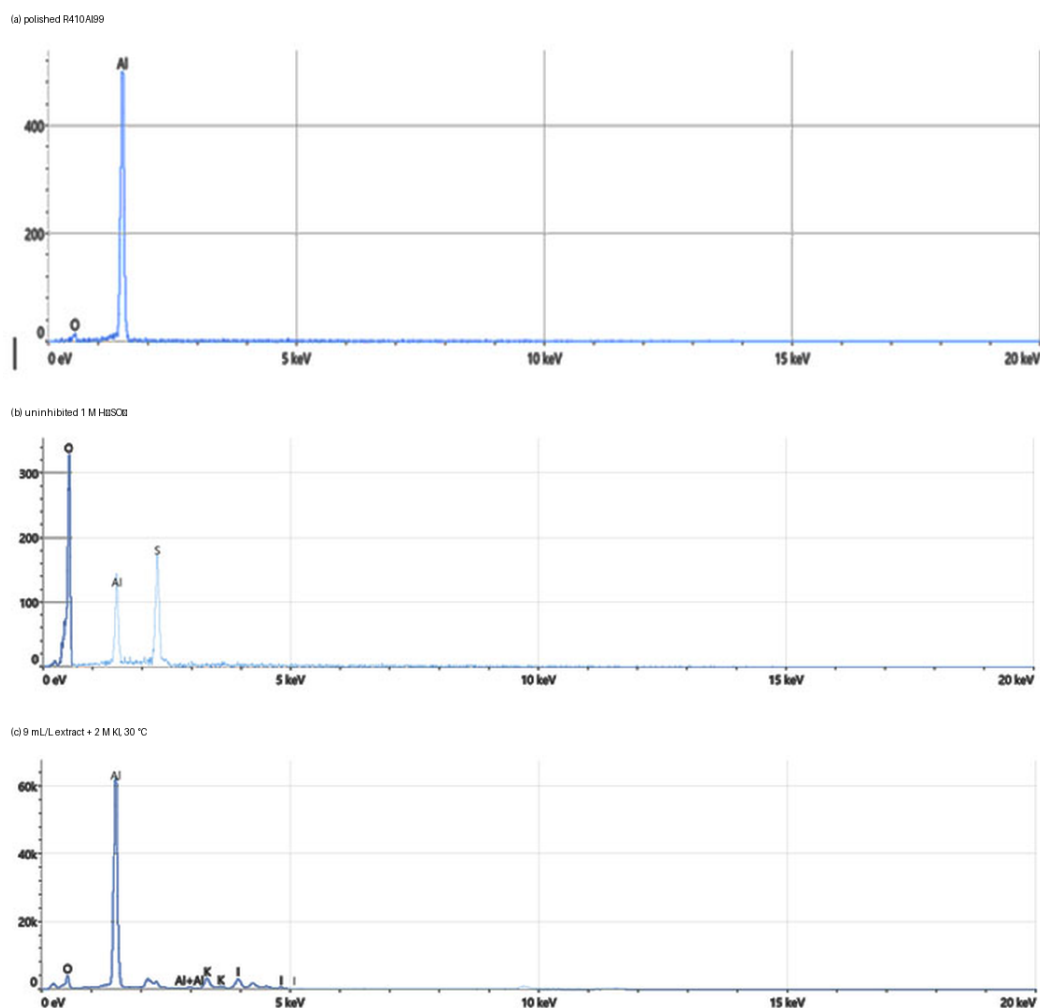


Fig. 6. EDS spectra of (a) polished R410Al99, (b) the uninhibited alloy after exposure to 1 M H₂SO₄, and (c) the alloy protected with 9 mL/L extract + 2 M KI at 30 °C.

Table 3. Semi-quantitative EDS composition of the investigated R410Al99 surfaces (atomic %).

Condition	Al	O	S	K	I
Polished alloy	90.3	9.7	ND	ND	ND
Uninhibited 1 M H ₂ SO ₄	9.9	72.9	17.1	ND	ND
9 mL/L extract + 2 M KI, 30 °C	64.4	29.1	ND	3.4	3.2

ND = not detected within the instrumental detection limit.

iodide [24].

FESEM analysis

The polished reference displayed relatively fine surface features. Uninhibited acid exposure produced a strongly irregular surface with obvious localized attack and features in the approximate 50–70 nm range. The KI-assisted inhibited specimen showed denser coverage and smaller measured features of approximately 47–52 nm in the imaged region, with fewer obvious corrosion pits than the uninhibited surface. Local heterogeneity remained, consistent with the thick deposit detected by AFM [25].

EDS analysis

The polished alloy contained 90.3 at.% Al and 9.7 at.% O, with no detectable S. Uninhibited exposure decreased the Al signal to 9.9 at.% and increased O and S to 72.9 and 17.1 at.%, respectively, indicating extensive coverage by oxygen- and sulfate-containing corrosion products. In contrast, the surface protected with 9 mL/L extract + 2 M KI contained 64.4 at.% Al and 29.1 at.% O; S was below the detection limit, while K and I were detected at 3.4 and 3.2 at.%. This composition supports reduced sulfate accumulation and retention of KI-derived species in the protective surface region [26].

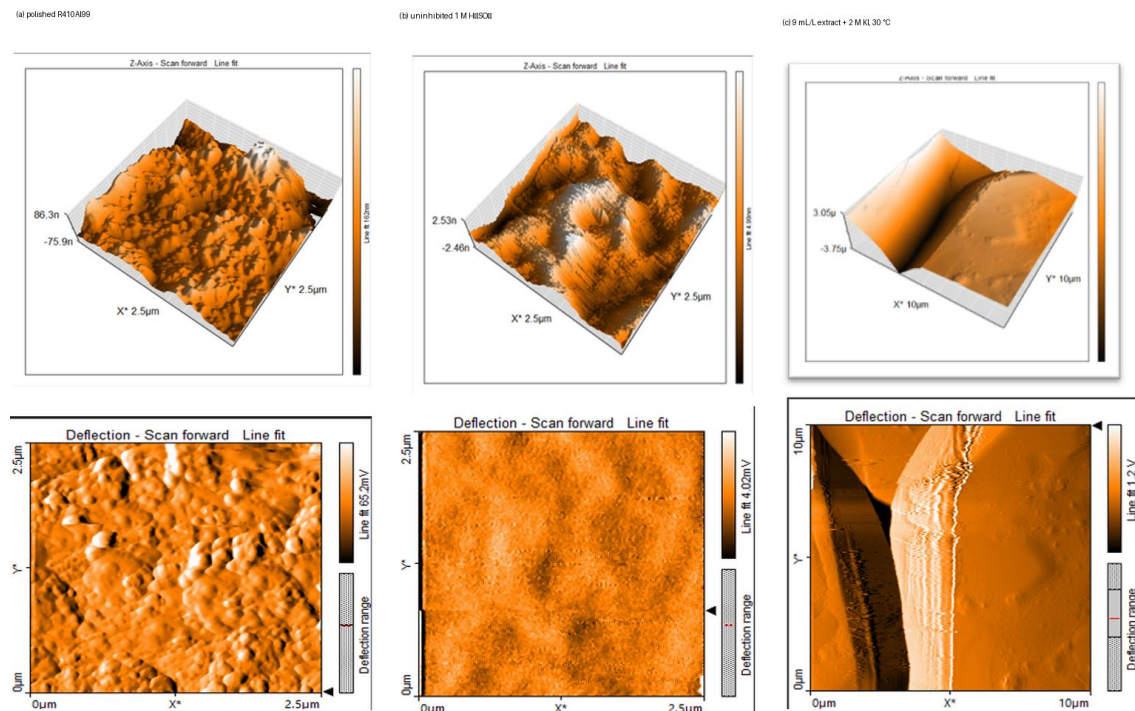


Fig. 7. AFM two- and three-dimensional topography of (a) polished R410Al99, (b) the uninhibited alloy after exposure to 1 M H_2SO_4 , and (c) the alloy protected with 9 mL/L extract + 2 M KI at 30 °C.

Table 4. Selected AFM roughness parameters for the investigated surfaces.

Condition	S_a (nm)	S_q (nm)	R_a (nm)	Vertical range
Polished alloy	17.198	23.241	13.889	191.9 nm
Uninhibited 1 M H_2SO_4	0.763	0.942	0.882	12.094 nm
9 mL/L extract + 2 M KI, 30 °C	1038.5	1380.2	1134.2	7.3696 μm

AFM analysis

The polished surface had $S_a = 17.198$ nm, $S_q = 23.241$ nm, and $R_a = 13.889$ nm. After uninhibited acid exposure, the corresponding values decreased to approximately 0.763, 0.942, and 0.882 nm. This apparent smoothing is attributed to preferential dissolution of polishing asperities and should not be interpreted as absence of corrosion. The KI-assisted inhibited surface showed much larger values ($S_a = 1038.5$ nm, $S_q = 1380.2$ nm, and $R_a = 1134.2$ nm) and a reported vertical range of 7.3696 μ m. The high roughness reflects a thick, heterogeneous adsorbed/deposited layer rather than a smooth exposed substrate [27].

The combined electrochemical results show that inhibition cannot be represented by a simple monotonic concentration law. Plant extracts are multicomponent systems, and increasing dose can improve coverage while also promoting aggregation, competitive adsorption, or desorption of weakly bound species. Temperature further changes oxide dissolution, inhibitor transport, and adsorption equilibria. Comparable concentration- and temperature-dependent behavior has been reported for other plant-derived aluminum inhibitors.

The complete Tafel matrix confirms that the optimum extract concentration changed from 15 mL/L at 10 °C to 9 mL/L at 20–30 °C and 6 mL/L at 40 °C. The direction of the corrosion-potential shift also changed with temperature and concentration, while both anodic and cathodic Tafel slopes varied. The system therefore affects both aluminum dissolution and the cathodic reduction process, with one branch becoming dominant under specific conditions. The pronounced positive shift at 30 °C/9 mL/L indicates anodic predominance for the surface-characterization condition, whereas the negative shifts at lower temperatures indicate stronger cathodic influence. The mixed directions at 40 °C reinforce that inhibition cannot be assigned to one fixed electrochemical mode.

The end-of-record OCP values provide an additional consistency check. For the Tafel-optimum concentration at each temperature, the OCP value differed from the fitted E_{corr} by only approximately 0.01–0.06 V. This close agreement strengthens confidence that the observed potential shifts were reproducible features of the interfacial state rather than isolated fitting artifacts. The large negative OCP displacements at 30 and 40 °C also show that the extract-iodide

layer substantially altered the mixed potential, although OCP direction by itself should not be used to rank inhibition efficiency.

The surface analyses provide a coherent mechanism for the KI-assisted effect. FTIR identifies O–H/N–H, carbonyl, aromatic/conjugated, and C–O-containing groups capable of coordinating or interacting electrostatically with the interfacial region. Iodide can adsorb specifically and modify the surface charge, facilitating retention of protonated or polar extract species [9,10]. Detection of K and I by EDS, together with the recovery of the Al signal and the absence of detectable S, supports formation of an iodide-containing organic-inorganic barrier that limits sulfate-rich corrosion-product accumulation.

AFM and FESEM describe different aspects of this barrier. FESEM indicates fewer obvious pits and finer features in the mixed system, while AFM records a large vertical range and high roughness. The latter does not imply greater corrosion by itself; it is consistent with a thick, non-uniform surface deposit. Correlating AFM with FTIR and EDS is therefore essential. Cyclic-polarization hysteresis further indicates that the film improves repassivation at selected conditions but does not eliminate localized-corrosion susceptibility across the complete concentration-temperature matrix. The persistence of positive loops for the 30 °C/9 mL/L and 40 °C/6 mL/L high-efficiency conditions is especially important: Tafel current suppression describes average uniform corrosion, whereas loop separation probes localized breakdown and repassivation. Hence, the inhibitor can be highly effective against general dissolution without completely eliminating pitting susceptibility.

[scan rate=2V/s, potential limits=−3V, stabilization time=900s, and number of replicate measurements=3].

A separate KI-only control would also strengthen quantitative evaluation of cooperative inhibition.

CONCLUSION

A combined inhibitor containing 2 M KI and methanolic *C. colocynthis* leaf extract effectively reduced the corrosion of R410Al99 aluminum alloy in 1 M H₂SO₄. Tafel efficiency depended strongly on concentration and temperature, reaching 99.77% at 6 mL/L and 40 °C. The 9 mL/L condition at 30 °C, used for detailed surface analysis, achieved 98.11% inhibition and reduced i_{corr} by more than one order of magnitude. End-of-record

OCP values agreed reasonably with the fitted E_{corr} values at the best-performing concentration for each temperature, providing cross-method consistency. Positive cyclic hysteresis persisted, however, including at the 30 °C/9 mL/L and 40 °C/6 mL/L high-efficiency conditions; the formulation therefore reduces general corrosion and supports repassivation but does not guarantee complete immunity to localized attack. FTIR, FESEM, EDS, and AFM collectively support formation of a chemically modified, iodide-containing, heterogeneous protective layer. The layer reduced sulfate-rich corrosion products, preserved the Al signal, and decreased obvious localized damage in the imaged region. The system acts through condition-dependent mixed inhibition, with anodic or cathodic predominance determined by temperature and extract concentration.

ACKNOWLEDGMENTS

The authors acknowledge the Department of Chemistry, College of Science, University of Diyala; the Nanotechnology Research Center, University of Technology; and the Al-Khora Technology Center, Baghdad, for laboratory and characterization support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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